

PROSPECTS FOR MEASUREMENTS OF CP VIOLATION AT HADRON COLLIDERS

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A brief review of the strategies used in looking for CP violation in B decays is presented. Some problems due to penguin diagrams are addressed. Penguin trapping is discussed, in the context of the upcoming experiments. The high rates and the possibility to perform experiments on the B_s system justify the interest in hadronic colliders.

1 Introduction

In the Standard Model, CP violation (CPV) arises from the clash of the Yukawa couplings with the charged current interaction. When the Lagrangian is written in the physical (mass) basis, this shows up as an irremovable phase in the CKM¹ quark mixing matrix. The magnitudes of most CKM matrix elements are constrained experimentally^{2,3}, and exhibit an hierarchy, with the magnitudes getting smaller as one leaves the diagonal. Together with unitarity, this motivates the Wolfenstein⁴ parametrization of the CKM matrix. The Wolfenstein parameters λ and A are known to 1% and 5%, respectively. The best (correlated) constraints on the Wolfenstein parameters ρ and η arise from the measurements of $|V_{ub}/V_{cb}|$ ⁵, $B^0 - \bar{B}^0$ mixing⁶, and the measurement of indirect CPV in neutral Kaons⁷.

These constraints depend on hadronic matrix “messy” elements, and hence have large errors. The corresponding allowed regions are shown in the figure, taken with the gracious permission of Neubert from his recent review². In this figure, the CP conserving measurements of $|V_{ub}/V_{cb}|$ and of $x_d = \Delta M/\Gamma$ (in the B_d^0 system) already imply CP violation. At present, this feature disappears if we take the most conservative bounds.

Another way to express these constraints is to look at the orthogonality of the first and third (db) columns of the CKM matrix. This can be written as

$$1 = \frac{V_{ub}^*}{\lambda V_{cb}^*} + \frac{V_{td}}{\lambda V_{cb}^*}. \quad (1)$$

The squared magnitudes of the two terms on the RHS are $\rho^2 + \eta^2$, and $(1 - \rho)^2 + \eta^2$, respectively, and the corresponding bounds lead to the two circular

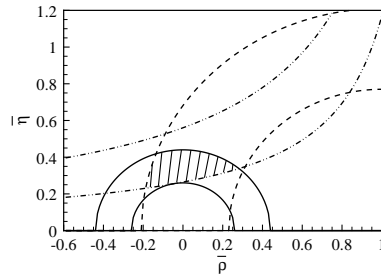


Figure 1: Constraints on the ρ - η plane. The circles centered at $(0,0)$ and $(1,0)$ describe the bounds on $|V_{ub}/V_{cb}|$ and x_d , respectively. The two hyperbolae arise from the CPV measurement in neutral Kaons.

sections in the figure. Equation 1 may be visualized as the well known unitary triangle in the $\rho - \eta$ plane. It is constructed from a side starting at $(0,0)$, another at $(1,0)$, and meeting at an apex lying within the allowed region in the figure. Its angles are uninspiredly known as α , β and γ , going clockwise from the apex. Increasing excitement is due to their upcoming measurement through CP asymmetries in B decays.

Depending on how the ϵ'/ϵ experiments develop, this might be the first independent measurement of CPV since 1964 (That was several years before I was born!!). In any event, it will help to constrain ρ and η , shedding new light on the structure of the CKM matrix and probing for New Physics effects.

2 Searching for CPV in B decays

Although CPV in the CKM matrix is a purely Electroweak phenomenon, since quarks are included, we are unavoidably confronted with strong interactions. These bring with them several new features:

- Though we can calculate reliably diagrams involving quarks and short-distance effects, the non-perturbative hadronic “messy” elements are not known to the desirable precision. This is responsible for the large errors in the figure, and, unless such matrix elements cancel out, also produces corresponding errors in B decays.
- Besides tree diagrams, we also get gluonic-penguins, which will complicate the analysis. There are also electroweak-penguins, which play a crucial role in certain decays⁸.

- Strong phases are induced by final state interactions. Two such phases are mandatory for direct CPV, but may obscure the interpretation of CPV from the interference between the mixing and the decay.
- Since the strong interaction preserves flavour, one may rephase the B^0 states. This means that only the clash between two phases may have physical meaning.

The last point leads to three classes of asymmetry observables:

1. *Indirect CPV*, where we clash the phases of the $B^0 - \bar{B}^0$ mixing mass (M_{12}) and width (Γ_{12}). We know that there is indirect CPV in the $K^0 - \bar{K}^0$ mixing, due to the measurement of the $\text{Re}(\epsilon)$ parameter. Unfortunately, this is expected to be unmeasurably small for the B_d and B_s systems.
2. *Direct CPV*, where we clash two independent decay paths. This requires at least two amplitudes (preferably of similar magnitudes), two different weak phases, and two different strong phases. If the final state is not common to B^0 and \bar{B}^0 , the decays have the advantage of being self-tagging. This is most clearly seen in B^\pm decays. In the kaon system, a measurement of ϵ'/ϵ would be a signal of this type of CPV.
3. *Interference CPV*, occurring when the final state is common to B^0 and \bar{B}^0 , where one clashes the direct decay path, $B \rightarrow f$, with the indirect $B \rightarrow \bar{B} \rightarrow f$ decay.

The first two methods are plagued by hadronic uncertainties. However, these cancel in interference CPV when the (common) final state is a CP eigenstate and the decay is overwhelmingly dominated by *one* weak phase. One finds,

$$a(t) = \frac{\Gamma[B^0(t) \rightarrow f] - \Gamma[\bar{B}^0(t) \rightarrow f]}{\Gamma[B^0(t) \rightarrow f] + \Gamma[\bar{B}^0(t) \rightarrow f]} = \zeta_f \sin(2\Phi) \sin(\Delta M t), \quad (2)$$

where ζ_f is the CP eigenvalue of the final state f , and Φ is the weak phase. One can also perform a time-independent measurement, thus paying a price of $x/(1+x^2)$. The measured value of x_d yields a modest suppression of 1/2. However, in the B_s system, the current lower bound on x_s ⁶ already implies a suppression of an order of magnitude. This is coming up on vertexing limits⁹, and makes time-dependent measurements mandatory for the B_s system.

The gold plated mode of this type is the $B \rightarrow J/\psi K_S$ decay, which measures $\sin(2\beta)$. This decay is important theoretically, because the penguin and tree contributions share the weak phase, and also experimentally, since the

J/ψ is easy to tag with di-leptons. Current estimates for BABAR and BELLE predict uncertainties of order 0.2¹⁰. At hadronic machines one has much higher luminosities, but also a much harder environment to work on. Comprehensive Monte Carlo simulations are still in their infancy. The fixed target HERA-B experiment quotes uncertainties around 0.13, while LHC-B quotes 0.023¹¹. In a very nice article, Butler¹² obtains 0.07, for the Tevatron running at 10³² luminosity¹³. I would like to thank him publicly for summarizing the effects of the various cuts and efficiencies in a complete and clear table (rather than scatter them all over 357 pages of jargon).

The hadronic mess reappears when one has more than one weak phase, as it happens in $B \rightarrow \pi^+\pi^-$, where the tree and penguin contributions come in with different phases. Here, besides the interference CPV $\sin(\Delta M t)$ term, we also get a direct CPV $\cos(\Delta M t)$ dependence. Even if there were no final state phases (in which case the cos term would vanish), the penguin diagram would still affect the extraction of $\sin(2\alpha)$ from the $B \rightarrow \pi^+\pi^-$ decay¹⁴. In fact, even for modest values of the penguin amplitude around 20% of the tree amplitude, we can find deviations of up to ± 0.4 in that determination¹⁴.

To remove this problem, Gronau and London¹⁵ have proposed the use of isospin symmetry to relate this decay to $B^0 \rightarrow \pi^0\pi^0$ and $B^+ \rightarrow \pi^+\pi^0$. Though one must also take the electroweak penguins into account¹⁶, these have been shown not to affect this method⁸. Unfortunately, the $B^0 \rightarrow \pi^0\pi^0$ branching ratio is of order 10⁻⁶ and we would have to detect two neutral pions in the final state. This is probably unfeasible at hadronic colliders. Still, we can use $SU(3)$ symmetry and relate $B^0 \rightarrow \pi^+\pi^-$ to the penguin dominated $B^0 \rightarrow K^+\pi^-$. Silva and Wolfenstein introduced this idea to “trap” the penguin¹⁷. In fact, once β is measured in $B^0 \rightarrow J/\psi K_S$, all we need is the rate ratio¹⁷, for which CLEO already has a (rather loose) bound¹⁸. Clearly, this technique will provide the first experimental handle on α . Recently, Gronau and Rosner¹⁹ have developed this idea, showing that one may remove the penguin factorization hypothesis by measuring in addition the branching ratio for $B^+ \rightarrow K^0\pi^+$. This also allows for the independent determination of γ , though β will be measured beforehand anyway (recall that $\alpha + \beta + \gamma = \pi$ in the SM; a fact used in all these analysis).

Another approach consists in constructing polygons relating various amplitudes to extract the CKM angles. For example, Gronau and Wyler²⁰ have suggested the extraction of the angle γ from triangles built using the $B^+ \rightarrow K^+(D^0, \bar{D}^0, D_+^0)$ decays, and their CP conjugates. Subsequently, Dunietz applied this strategy to neutral decays²¹, in what the LHC-B collaboration calls Method Two²². For simplicity, I will use their notation. Method One is due to Aleksan, Dunietz and Kayser²³ and uses B_s decays into $D_s^\pm K^\mp$. One

may also combine these polygon constructions with $SU(3)$ symmetry²⁴ to extract the angles of the unitarity triangle. Such techniques have been further explored in a very large number of recent articles.

3 The use of the B_s system

An important constraint on the parameters ρ and η would come from a measurement of the mass difference between B_s^0 and \bar{B}_s^0 , Δm_s . Looking at figure 1, we realize immediately that the constraint on $|V_{td}|$ arising from Δm_d is rather poor. This is due to the hadronic uncertainties : the bag term and the decay constant for B_d are only known to about 20%. However, their ratios to the corresponding factors for B_s are much better known. Therefore, a clean determination of $\Delta m_s/\Delta m_d$ would greatly improve our knowledge of the CKM matrix. The current LEP limit²⁵ is $\Delta m_s > 7.7\text{ps}^{-1}$, and the reader is encouraged to ask them about the meaning of the 8ps^{-1} minimum in the likelihood plot. Should this value become much higher, we might run into technology limits⁹. Moreover, when looking for asymmetries in B_s^0 decays, the oscillations in equation 2 will become too fast for detection.

Fortunately, the width difference between B_s^0 and \bar{B}_s^0 might come to the rescue. In a recent analysis, Beneke, Buchalla and Dunietz²⁶ find

$$\left(\frac{\Delta\Gamma}{\Gamma}\right)_{B_s} = 0.16^{+0.11}_{-0.09}. \quad (3)$$

Hence, the width difference cannot be neglected, and the decay rates may be written as

$$\begin{aligned} \Gamma[B \rightarrow f] &\propto H(\Delta\Gamma t/2) + I(\Delta M t) \\ \Gamma[\bar{B} \rightarrow f] &\propto H(\Delta\Gamma t/2) - I(\Delta M t). \end{aligned} \quad (4)$$

For untagged decays, not only is there no statistics cost from tagging, but the rapid oscillation $I(\Delta M t)$ terms drop out. Strictly speaking, one should now talk about the short lived and the long lived B_s states. As pointed out eloquently by Dunietz²⁷, this provides a uniquely different way to measure CPV in the B system. In particular, Method One is applicable with untagged samples. Dunietz²⁷ also proposes an untagged B_s into $D^0\phi$ version of Method Two. This is a hot topic, and rapid new developments are expected.

4 Conclusions

The fact that the SM has only one CPV independent quantity makes it very predictive, giving us an ideal setting in which to look for the Physics Beyond.

Since thirty two years is a lot of time to seat on our hands, this picture should (and will) be tested.

In the B system, the first information will be the measurement of β in the gold plated $B \rightarrow J/\Psi K_s$ decay. For a measurement of α in $B \rightarrow \pi^+\pi^-$ we must trap the penguin. This can be performed¹⁷ comparing it to $B \rightarrow K^+\pi^-$, and we can avoid the penguin factorization approximation¹⁹ by measuring in addition $B^+ \rightarrow \pi^+K^0$. As for the extraction of γ , there are several classic methods^{20,21,23}. The good news from Duniety²⁷ is that we may be able to use untagged samples for Method One²³, and for the B_s into $D^0\phi$ version of Method Two²⁷. This is specially interesting if the width and mass differences in the B_s system turn out to be large.

The angle β will soon be measured at BABAR, BELLE and HERA-B. We will also learn a considerable amount about penguin trapping. The high rates and the (complementary) B_s Physics opportunities available at the Tevatron and LHC warrant dedicated B-Physics experiments. Understanding the real capabilities of such experiments, under what is admittedly a very hard environment, will require extensive Monte Carlo simulations. Please summarize each step of your cuts and efficiencies clearly. We will thank you for it.

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